About the modern "experimental value" of W boson width.

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Abstract

It is shown that the methods which have been used up to now to determine the W width from the $p\bar{p}$ data confirm the SM predictions for some combinations of various phenomenological parameters, however, they do not give an independent value for the W width. Moreover, the accuracy that could be achieved in future experimental checks of SM predictions for such quantities is limited by effects which require detailed theoretical study.

Introduction

Recent results from LEP and SLC have given us a value for the mass and the width of Z boson with a spectacular precision. The same problem for W boson is studied at the Fermilab $p\bar{p}$ collider.

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In this note, we discuss experimental results related to the W–boson decay width Γ_W. These have been obtained by CDF and D0 collaborations by two methods – the "indirect" (see [1]) and the "direct" one [2],[3]. These results are in agreement with each other. They confirm the Standard Model (SM) with 3 families including a top quark much heavier than the W boson. The value of Γ_W obtained in these measurements is quoted now in Particle Data Review [4].

Even if we assume that our knowledge of the quark distribution functions in the proton is precise enough, the results of the experiments just mentioned are described by some complex relations, containing both Γ_W and other quantities, which can be determined only by the use of the SM, either explicitly or implicitly. Hence, these experiments check SM predictions in this form only.

Consequently, the results of these experiments can not be treated as the independent experimental value of the W boson width.

Due to the fact that *(i)* the results of these experiments are expressed through a number of phenomenological parameters of the SM and *(ii)* New Physic can manifest itself in various ways, i.e. influence all the SM parameters used for the width extraction from the data, the analyses of possible New Physic manifestation in these experiments by looking for the deviations from the SM in Γ_W *only* seem to be meaningless. Besides, possible improvement of the accuracy of such SM confirmation is limited by our insufficient knowledge of the parton distributions in the proton and by some nontrivial radiative corrections.

To explain these statements, we *(i)* briefly reproduce ideas of the methods [1, 2] without making any criticism ; *(ii)* consider the real relation between the data obtained and the SM; *(iii)* briefly discuss difficulties with the possible improvement of the confirmation of the SM within these methods.

Main points of the experimental methods.

In both methods, W production is recorded as an event with production of a lepton (for example, electron) having high transverse momentum. A large transverse energy imbalance is required to signal the presence of a neutrino.

"Indirect" method.

This is the "eldest" method which has been used to obtain Γ_W from the data. The value of Γ_W obtained by this method is quoted now in [4]. One can find a detailed description in ref. [1].

In this method, the experiment gives the total number of "real" W's produced which have then decayed into e.g. $e\nu$ (with necessary cuts). The number of events is written as the product of the W boson production cross section $\sigma(W)$, the corre-

sponding branching ratio and total luminosity L:

$$N_{W/e} = L \cdot \sigma(W) \cdot Br(W \to e\bar{\nu}) \tag{1}$$

The production cross section $\sigma(W)$ is calculated using known structure functions in the standard way, assuming that the coupling of the quarks to the W boson is given by the SM.

The production cross section $\sigma(W)$ and the luminosity L are known with bad accuracy. To circumvent this problem, the production of e^-e^+ pairs with high transverse momentum is also considered, these events occur through the production and subsequent decay of Z-boson. The number of events of this type is written similarly:

$$N_{Z/e} = L \cdot \sigma(Z) \cdot Br(Z \to e^-e^+).$$

The observed ratio of $N_{W/e}$ and $N_{Z/e}$

$$\frac{N_{W/e}}{N_{Z/e}} = \frac{\sigma(W)}{\sigma(Z)} \cdot \frac{Br(W \to e\bar{\nu})}{Br(Z \to e^-e^+)} \tag{2}$$

is free from a number of inaccuracies which are inherent to both quantities $N_{W/e}$ and $N_{Z/e}$ if they are treated separately. Indeed, the poorly known luminosity factor, L, has dropped out. Second, the ratio of production cross sections is calculated with high accuracy because these cross sections are defined by the same structure function. The effect of radiative corrections to these cross sections is beyond the accuracy of this calculation.

Since $Br(Z \to e^-e^+)$ is known precisely from the LEP data, the above ratio gives $Br(W \to e\bar{\nu})$. However, in order to extract the value of the W width from the data one needs extra input. The assumption that the partial width $\Gamma(W \to e\bar{\nu})$ is just given by the SM is used for this aim. Finally,

$$\Gamma_W = \Phi \frac{N_{Z/e}}{N_{W/e}}; \quad \Phi = \frac{\Gamma(W \to e\bar{\nu})}{Br(Z \to e^+e^-)} \Sigma(W/Z); \quad \Sigma(W/Z) = \frac{\sigma(W)}{\sigma(Z)}. \tag{3}$$

In more details, the factor $\Sigma(W/Z)$ is written:

$$\Sigma(W/Z) \propto \frac{\nu(u\bar{d}/u)\Gamma(W \to u\bar{d}) + \nu(c\bar{s}/u)\Gamma(W \to c\bar{s})}{\sum\limits_{q=u,d,s,c,b} \nu(q/u)\Gamma(Z \to q\bar{q})}. \tag{4}$$

Here quantities ν are expressed through the quarks and antiquarks distribution functions in the proton, for instance,

$$\nu(u\bar{d}/u) = \frac{< n_u(x_1) n_{\bar{d}}(x_2)|_{x_1 x_2 = M_W^2/s} >}{< n_u(x_1) n_{\bar{u}}(x_2)|_{x_1 x_2 = M_Z^2/s} >}, ...; \ (\nu(u/u) = 1), \tag{5}$$

where <> means averaging with the use of the experimental cuts.

Some additional assumptions make possible further simplifications for the ratio of the cross sections $\Sigma(W/Z)$. For example, one can neglect the contribution of charmed quarks. In this case, the numerator of this ratio contains only the first term, while the denominator has three terms, which correspond to u, d, s quarks. The quantity $\Gamma(W \to u\bar{d})$ has to be calculated within the SM together with $\Gamma(W \to e\bar{\nu})$.

Since the factor Φ is calculated with good precision, equation (3) give us the "experimental" value of Γ_W.

"Direct" method.

Another approach to the Γ_W measurement has been proposed in ref. [3]. This method with little modifications has been recently used by CDF group [2].

The idea is to study the production of $e\nu$ system, with an invariant mass Q which is larger than some value $Q_0 \gg M_W$ and to compare it with $W(e\nu)$ production, described by eq. (1)[1]. It is assumed that all these events are generated via the production of highly virtual W bosons. The number of events is given by the approximate equation (similar to the equation, proposed in ref. [6] for the *narrow* region near Z pole):

$$N(Q) \propto L \cdot \int\limits_{Q^2 > Q_0^2} dQ^2 \sigma(W,Q) \frac{Q^2 \Gamma(W \to e\nu)}{(Q^2 - M_W^2)^2 + \Gamma_W^2 \cdot (Q^2)^2 / M_W^2}, \tag{6}$$

where integration over other parameters with suitable kinematical cuts is assumed.

In this equation $\sigma(W,Q)$ stands for the production cross section of the off-shell W and a specific form of Q^2 dependence for the W width (both total and partial) is assumed. To calculate $\sigma(W,Q)$ the same approximation for partial decay widths of the W to quarks is used and the convolution of the distribution functions in the new point Q^2 is evaluated.

Then, similarly to the "indirect" method, one considers the ratio of the quantities described by eq. (6) and eq. (1). Since $\Gamma(W \to e\bar{\nu})/Br(W \to e\bar{\nu}) = \Gamma_W$, this new ratio is written in the form

$$\frac{N(Q)}{N(W/e)} \propto \int\limits_{Q^2 > Q_0^2} dQ^2 \frac{Q^2 \Gamma_W \Sigma(Q)}{[(Q^2 - M_W^2)^2 + Q^4 \Gamma_W^2 / M_W^2] M_W}; \; \Sigma(Q) = \frac{\sigma(W,Q)}{\sigma(W)}. \tag{7}$$

Here, the factor $\Sigma(Q)$ is calculated with the same (or better) accuracy as in ratio (2). Indeed, just as for the "indirect" case, we have

$$\Sigma(Q) = \frac{\nu(u\bar{d}/u;Q)\Gamma(W \to u\bar{d};Q) + \nu(c\bar{s}/u;Q)\Gamma(W \to c\bar{s};Q)}{\nu(u\bar{d}/u)\Gamma(W \to u\bar{d}) + \nu(c\bar{s}/u)\Gamma(W \to c\bar{s})}. \tag{8}$$

[1] In the actual experiment [2] the transverse mass of the $e\nu$ system is used rather then the invariant mass. A cut in the transverse mass $M_\perp > 110$ GeV is imposed.

The new notations are evident from a comparison with eq. (5).

Using the extrapolation for partial widths in the spirit of ref. [6] and neglecting c quark content in the proton, this quantity transforms into the ratio of quark numbers at different x, and the final equation (7) does not contain any term calculated in the SM.

Hence, the ratio of events (7) depends only on one unknown quantity: the total width Γ_W. Therefore, the value of Γ_W is obtained by fitting the data with this equation.

Relation to the Standard Model and the effects of New Physics in experiments.

Indirect method. The analysis after eq. (3) shows that the SM has been used repeatedly for the calculation of the quantity Φ in the right hand side of this equation. It is necessary to calculate both $\Gamma(W \to u\bar{d})$ and $\Gamma(W \to e\bar{\nu})$, however these calculations have the same status as the calculation of Γ_W. They rely on an assumption about the existence of three families with a very heavy t–quark [2]. Moreover, the partial widths of Z decay into various light quark systems have not been measured separately. Hence, they are calculated within the SM only. Therefore, the indirect method gives some combination of various phenomenological parameters, but not Γ_W separately.

Direct method. At first glance, we deal here with a much better situation. Indeed, SM calculations in this case have dropped out from the ratio of the cross sections $\Sigma(Q)$. Unfortunately, this conclusion is inexact. Indeed, the crucial point of this method is the use of the W propagator in the specific form (6) and the corresponding extrapolation for W partial widths. The equation used for the propagator has been proposed in ref. [6] as an approximation which is valid near the W pole only. It was not proven for the case $Q^2 \gg M_W^2$ discussed here. Hence, the basic equation (6) above is unfounded. To obtain the correct form of the corresponding cross section, the radiative corrections should be taken into account both to the W propagator itself (real part of its polarization operator) and to the partial widths of W decay to leptons or quarks, which are latent in the final result. In particular, new channels (like $W^* \to t\bar{b}$, $W^* \to W\gamma$) contribute more and more strongly to the effective total W width $\Gamma_W(Q)$ with the growth of Q.

Even if one would take these points into account, the basic problem will still be there: just as in the indirect method we use SM predictions for some basic quantities in the equations. Therefore, the "direct" method gives us in fact some

[2] Certainly, at the modern level of the SM verification the leptonic widths have been calculated in tree approximation of SM, while for the quark widths one–loop gluon corrections [7] have been taken into account.

complex object (which *as a whole* can be predicted by the SM) but not the value of Γ_W separately.

Relation to the New Physics Effects. The main goal of similar work is to look for possible deviations from the SM – effects of the New Physics. These effects can show up in various ways, i.e. they can change all quantities used for the description of the experiments discussed (the modifications in Γ_W is only one possibility with a lot of the others being neglected in the basic equations due to the use of the SM).

To make this point more clear, we present some partial list of opportunities. Perhaps, some of them are excluded by other data, but in each case special study is needed in order to ignore a particular model in the analysis of the experiments discussed.

For example, one can imagine that there is some small additional fraction of observed high $p_\perp$ leptons due to their production in the decay of selectron or smuon or excited electron or muon or any other particle with high enough mass, which can be produced either directly (via photon or Z) or through W decay. Besides, some new thresholds could be opened with the increase in the effective mass Q of the produced $W \to e\nu$ system (both standard ($t\bar{b}$) and "non–standard" channels). They can increase total W width and decrease visible leptonic Branching Ratio. This effect is particularly dangerous in the "direct" method. Similar effects can be connected with the admixture of additional heavy W bosons (from some extension of SM).

The accuracy of possible forthcoming confirmations of the SM in these methods.

It seems that the experiments which have been discussed so far provide a good place for the test of the SM predictions for the ratios of the number of events. For example, CDF group believes that in the framework of the "direct" method "... with future runs of the Fermilab collider, a 30 MeV measurement (of W width) is possible which approaches the level of the radiative corrections to the width."[2].

The statement about the measurement of Γ_W has already been discussed above, but the aim to achieve an accuracy of $\sim 1\%$ in these experiments (which is indeed the level of the SM electroweak corrections) introduces further problems. Unfortunately, there is no theory that can describe the data with such accuracy even within the SM. Let us discuss briefly the difficulties associated with the proposed level of accuracy.

First of all, the W transverse momentum distribution enters the actual data analyses [2]. The contribution of the region of small $p_\perp$ in this distribution is very important, but now it can only be obtained with poor accuracy, especially for $p_\perp \leq$ 10 GeV. This leads to an uncertainty in the final result which has been estimated as $\sim 2\%$ for the "indirect" method [5]. For the "direct" method this uncertainty has

not been discussed yet. Besides, gluon radiation and processes like $s+g \to W+c$ should vary the W distribution over $p_\perp$ with an increase in Q. These effects should be taken into account in the precise analysis of the results obtained by the direct method. Finally, inaccuracy due to the ignorance of the c quark contribution should be estimated too.

Let us assume however that this difficulty can be overcome. If so, more delicate questions, connected with the calculation of radiative corrections to the basic process $p\bar{p} \to W + ... \to e\nu + ...$, become important and require additional theoretical work. Let us mention only two of them.

(i). With higher accuracy, simple Breit–Wigner description of the unstable gauge boson propagators becomes inadequate for different reasons. For example, the difficulties connected with the gauge invariance have been recently pointed out for e^+e^- and $\gamma\gamma$ collisions [8]. Hence, methods like those developed in refs. [9] have to be used at least.

(ii). QCD radiative corrections to the W production process give here the Q^2 dependent K – factors (similar to the standard Drell–Yan process description). The new point here is the fact that the electromagnetic corrections should be taken into account in these K – factors since W boson is the charged particle in contrast to the photon.

Therefore, *the experimental value for the width of the W boson* Γ_W *is absent now*. We don't see any method for the determination of this width before LEP2 operations.

Nevertheless, the expected precision in the confirmation of the SM in the experiments discussed is remarkable. Perhaps, it will be useful to consider them as new experiments for testing QCD and proton structure.

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References

[1] See e.g. J.P. Repellin. In "Physics in Collision" 11, Ed. Frontiers (1991).

[2] F. Abe et al. (CDF collab.) Phys. Rev. Lett. **74** (1995) 341.

[3] J.L. Rosner, M.P. Worah and T. Takeuchi. Phys. Rev. **D49** (1994) 1363.

[4] Particle Data Group. Phys. Rev. **D50** (1994) 1173.

[5] M.H. Reno. Phys. Rev. **D49** (1994) R4326.

[6] F.Berends. In "Z Physics at LEP 1", CERN Yellow book. CERN-89-08 (1989) p.89.

[7] A. Djouadi and P. Gambino. Phys.Rev. **D49** (1994) 3499, 4705.

[8] A. Aeppli, F. Cuypers and G.J. van Oldenborgh. Phys. Lett. **B314** (1993) 413.

[9] R. Stuart Phys.Lett. **B262**(1991),113
A. Aeppli, G. Oldenborgh and D. Wyler. Nucl. Phys. **B428** (1994) 126.